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Liquid Rocket Engine Test Stand Planning Methodology

J. L. Emdee
The Aerospace Corporation, United States
emdee@aero.org

M. J. Adams
The Aerospace Corporation, United States
michael.adams@aero.org

S. Rahman
NASA - Stennis Space Center, United States
shamim.a.rahman@nasa.gov

ABSTRACT

The testing of liquid propulsion engine systems is a significant element of launch vehicle development. To take a proactive step in U.S. test center planning, U.S. liquid rocket engine test needs were evaluated and roadmaps were developed. To start this process, interviews were held with industry and government planners to understand program goals and needs. This information was then used to develop program architectures and propulsion needs. Previous rocket engine development efforts over the last 20 years were reviewed to estimate expected test rates for new component and engine programs. These test rates and programs architectures were used to generate best estimate roadmaps for propulsion test needs. Test roadmaps were developed for both existing flight programs as well as anticipated programs for hydrogen and hydrocarbon liquid engines with 45 KN (10,000 lbf) thrust and higher. The process for development of the test roadmaps is discussed, as well as the impacts of these programs on the test infrastructure. The process is illustrated using the NASA space exploration vision as an example.

INTRODUCTION

Ground testing of liquid propulsion engine systems has traditionally represented a significant portion of launch vehicle development time and cost. There are a variety of reasons for testing rocket engines and their components, some of which are:

- To validate design, analysis, manufacturing workmanship and modification.
- To demonstrate thrust (throttling), mixture ratio excursion and performance capabilities.
- To characterize system/component behavior at design point and off-design conditions, transients and steady state, and to determine acceptable limits (margin) for parameter values.
- To experimentally determine the thermochemical, heat transfer and structural performance, and compare results with analytical models and design tools for their validation and refinement.
- To determine and/or demonstrate repeatability, durability and restart/turn-around time capability.
- To characterize and demonstrate combustion stability and feed system coupled instability behavior.
- To understand component and subsystem performance in an integrated environment and the relationship between control system inputs and key engine parameter responses.
- To obtain data on wear rates and servicing requirements, especially for RLV engines.
- To determine vehicle stage/engine interface compatibility.

Advances in analytical capabilities have reduced the extent to which one has to test a new system to understand its operation and its failure modes. However, ground testing will remain a critical risk reduction requirement for any development program.

To help determine future test needs, a study was conducted in 2004 on the future utilization of domestic liquid rocket engine (LRE) test facilities.[1] That study used historical data to estimate anticipated program needs for both new and evolved boost and upper stage engines. The study also examined LRE test capabilities against the projected propulsion system development needs out to the year 2020. The primary focus was on LOX/hydrogen and LOX/hydrocarbon engines and major components in the thrust-class of 45 KN (10 Klbf) and higher.

The study was conducted in three steps: definition of expected propulsion system requirements based on program goals; development of representative test requirements for each program; and examination of current domestic engine test capabilities against the time phased engine development needs. The test planning process in the first two steps is discussed in this paper. The final step is discussed only in summary and more details can be found in Refs. 1 and 2.

DEFINITION OF EXPECTED PROPULSION SYSTEM REQUIREMENTS BASED ON PROGRAM GOALS

Current Propulsion Programs

The current U.S. space launch market is dominated by military and civil launch needs. The commercial space launch market is improving, but remains a small driver in determining propulsion test needs at U.S. test centers. The EELVs, or Evolved Expendable Launch Vehicles (Delta IV and Atlas V), are expected to remain in continuous production over the next couple decades. Engine and component test needs for the EELV program will be primarily limited to engine acceptance and anomaly resolution. The Atlas V vehicle uses a Russian produced RD-180 engine that is acceptance tested by the supplier, NPO Energomash, in Russia. An RD-180 U.S. co-production effort between NPO Energomash and their U.S. partner, Pratt & Whitney is underway. However, domestic test needs flowing from that co-production effort still remain to be defined. The Delta IV launch vehicle uses a domestically produced Rocketdyne RS-68 engine that is currently tested at NASA Stennis Space Center in Mississippi. Both Atlas V and Delta IV upper stages use RL10 variants produced and tested at Pratt & Whitney, West Palm Beach. The Air Force Titan IV launch vehicle will be retired this year. Delta II is estimated to be phased out by 2009 and engine test needs begin to diminish this year. The Space Shuttle Transportation System is scheduled for retirement in 2010. Anticipated propulsion test needs through 2020 for these operational launch vehicles are shown in Figure 1.

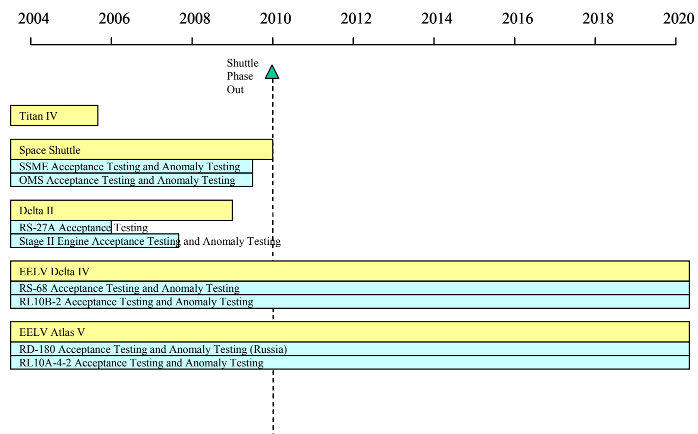

Figure 1. Operational launch system liquid propulsion test needs.

Future Propulsion Programs

The U.S. government has announced several new spacelift initiatives that span the next two decades. Programs in work with potentially significant liquid engine testing needs include the NASA Project Constellation exploration initiative, the joint FALCON (Force Application and Launch from the Continental US) demonstration program, the USAF ARES (Affordable Responsive Spacelift) program, the on-going IHPRPT (Integrated High Payoff Rocket Propulsion) technology programs, and potential upgrades to existing systems. The specific mission needs and associated implementation planning for these efforts remain undefined at this time, but estimates were made to develop several liquid propulsion test scenarios. To illustrate the process, the test needs for the NASA exploration program will be discussed. Military programs will be discussed in a separate paper.[2]

Commercial rocket development efforts continue to make progress. For example, Space X is readying their first launch using newly developed kerosene engine systems and Blue Origin is developing a hydrogen peroxide system. Other developers, like Scaled Composites, are using hybrid systems. In reviewing these programs, it was determined that their impact on the domestic test market will be limited for the near future. However, this could change significantly if commercial spacelift requirements increase.

NASA Space Exploration Vision Description

In January 2004, President George W. Bush laid out a vision for long-term space exploration to be carried out by NASA.[3] This vision included return to the moon as a step toward eventual Mars missions. NASA is currently planning the implementation of that vision and is expected to develop and revise the architecture over the next year[4-15]. The launch systems architecture revolves around Project Constellation, which includes a Crew Exploration Vehicle (CEV), landing and ascent vehicles, and transfer stages. The earth-to-orbit launch systems are expected to include a Crew Launch Vehicle (CLV) used to launch the CEV and a new Heavy Lift Vehicle (HLV) for lunar operations. Cargo transportation will be handled primarily by EELV vehicles and any newly developed commercial capabilities.[16] The final architecture is in flux but may include combinations of the launch options listed above.

Milestones for space exploration were estimated in Figure 2 based on announced desires to accelerate CEV deployment. Although it may be desirable to have the CEV operational before Shuttle is retired in 2010, given historical development efforts, the timeline shown appears more reasonable and represents a two-year advancement over the originally announced schedules. These milestones were used to develop four possible system architectures: Shuttle derived, EELV derived, EELV derived with new booster engines, and foreign derived. New clean sheet designs were ruled out based on cost and schedule constraints. Recent announcements indicate that NASA may prefer a CLV consisting of the Space Shuttle Reusable Solid Rocket Booster (RSRB) with a new upper stage and an HLV that is shuttle derived.[16] In order to determine the propulsion system needs, literature searches[3-24] and interviews with users and suppliers were used to determine possible future directions. Some of the findings are discussed below.

The space exploration program is likely to be heavily cost constrained and reliant upon evolutionary technology approaches with each advancement in capability. These constraints rule out revolutionary propulsion designs. It may even rule out new conventional booster engines. A new high thrust upper stage engine or multiple engines based on current designs will likely be required for increased lift capability.

- **2008 First robotic missions to the moon**
- **2010 Shuttle retirement**
- **2010 First unmanned CEV flight**
- **2012 First manned CEV flight**
- **2014-2018 Human moon missions**
- **2030 Human mars mission**

Figure 2. NASA Space Exploration milestones.

Use of non-toxic propellants will likely be required on the CEV and other in-space systems. Non-toxics improve operations and safety and will reduce launch costs. This will require development of a non-toxic Reaction Control System and eventually non-toxic orbit transfer systems and propulsion for lunar lander and ascent systems. There is evidence that methane may be considered as a fuel as well as hydrogen for the orbit transfer, lander, and ascent systems.[8-9,13] Methane has the advantage that future Mars in-situ propellant development may be applicable with this fuel, and experience with methane propulsion early on may reduce risk in the future. LOX/alcohol, considered for Shuttle upgrades in the past, is also a possible candidate for these systems. Alcohol has been used for a crew escape system demonstration.[18]

Human rating is a significant driver in the testing requirements for the propulsion systems and launcher system. Although there are no propulsion specific guidelines for human rating, NASA design guidelines[19-20] have been reviewed to gain some insight into the impact on propulsion hardware test. In addition, reports on engine and vehicle testing were reviewed.[21-24] The following findings on human rating are shown below.

- “All critical systems essential for crew safety shall be designed to be two-fault tolerant.

When this is not practical, systems shall be designed so that no single failure shall cause loss of the crew".[19] For engines, the former guideline can be accommodated with health monitoring system and an engine out capability. At the vehicle level, human rating might be met by a crew escape system requirement to mitigate loss of life. Additional risk mitigation would include engine design changes to improve marginal components and test verification of those changes.

- "Military Standard 1540[21], Test Requirements for Launch, Upper-Stage and Space Vehicles … or equivalent component qualification and acceptance testing standards should be used as guidelines".[20] This implies environmental qualification tests may need to be performed on engine components such as valves and engine controllers.

- "Vehicle reliability must be verified by test".[19] There will be emphasis placed on health monitoring and fault detection to improve system reliability. This will likely have an impact on engine testing. Large test databases will be required to map out engine behavior under all flight conditions so that the software can properly act on any anomalous readings. The SSME program had over 100,000 seconds of firing prior to first flight. A large part of this was to overcome technical challenges, but this is significantly larger than ~20,000 seconds of test time for recent engine programs.[23] Reference 23 recommends 40,000 seconds of firing and 400 tests for high reliability engine programs. Fiscal constraints will require smart testing in the future to reduce cost.

- Integrated systems testing may be required for an expendable system, as well as future crew lander and transfer vehicle applications. Stage acceptance firings were standard practice during the Apollo program.[24] These were used to verify the integrated system.

Potential vehicle development schedules out to 2020 were derived from the above information to estimate liquid engine test needs for the four architectures mentioned earlier. In all but the foreign derived architectures, it was assumed that a new human rated upper stage engine would eventually be needed for higher thrust needs compared to the RL10. The EELV and Shuttle derived architectures will be discussed further as examples.

The EELV derived launcher concept for human flight (Fig. 3) is based on the assumption that the EELV vehicle will be evolved to accommodate human rating and increased performance. This concept includes a wide body upper stage and eventually adds a wide body HLV booster to accommodate multiple existing engines for higher thrust and engine out capability.[14-15] The initial flights are assumed to be performed with multiple RL10s at lower capability, until a new engine is developed. This approach is similar to the Saturn IB to Saturn V evolutionary path.

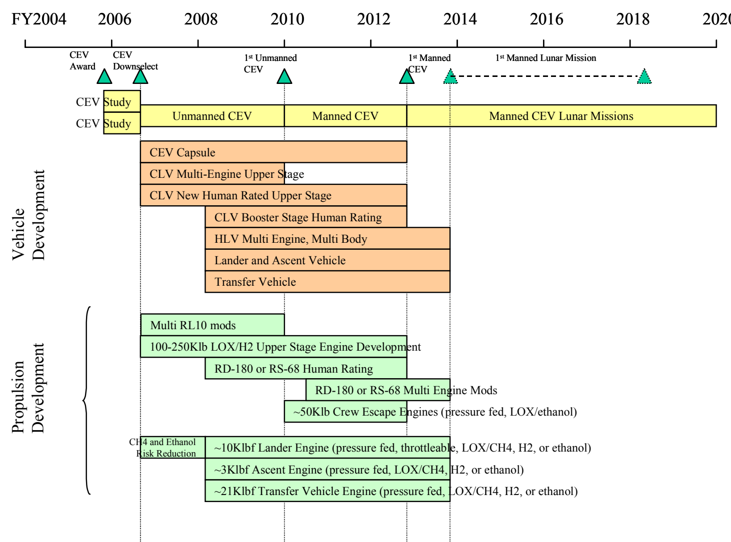

Figure 3. Project Constellation EELV Derived.

The Shuttle derived concept (Fig. 4) assumes that the CLV is accommodated with a single RSRM (Reusable Solid Rocket Motor) and new upper stage. The HLV is accommodated by the Shuttle system, but the orbiter is replaced with a new stage to accommodate the CEV and transfer stage similar to a Shuttle-C configuration. In addition, it is assumed that the SSME engines are replaced with less expensive, higher thrust, but human rated, RS-68 engines. This is just one of many possible Shuttle derived architectures. If SSME engines were used, less testing would be anticipated.

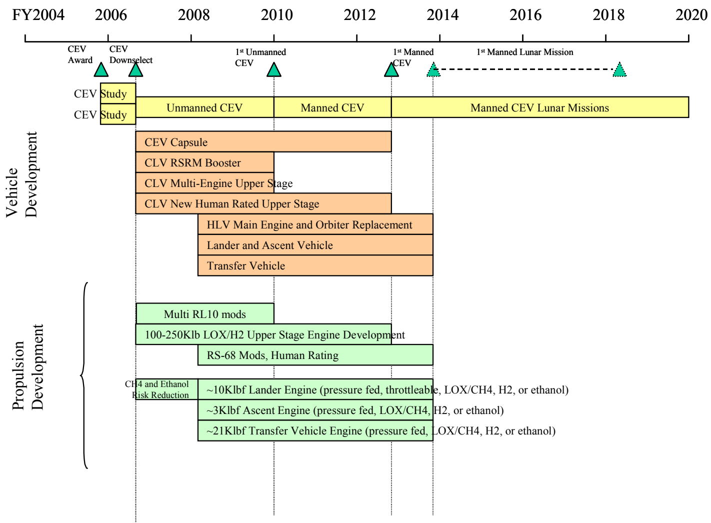

Figure 4. Project Constellation Shuttle Derived

The third concept is based on an assumption that human rating will be required to be built into new engines and vehicles rather than added to an existing vehicle. This requirement is met in an EELV evolved architecture with new engines (Fig. 5). This approach requires the most extensive propulsion development. Possible options are 1-Mlbf thrust class ox-rich staged combustion (ORSC) kerosene engines or full flow staged combustion (FFSC) hydrogen engines.

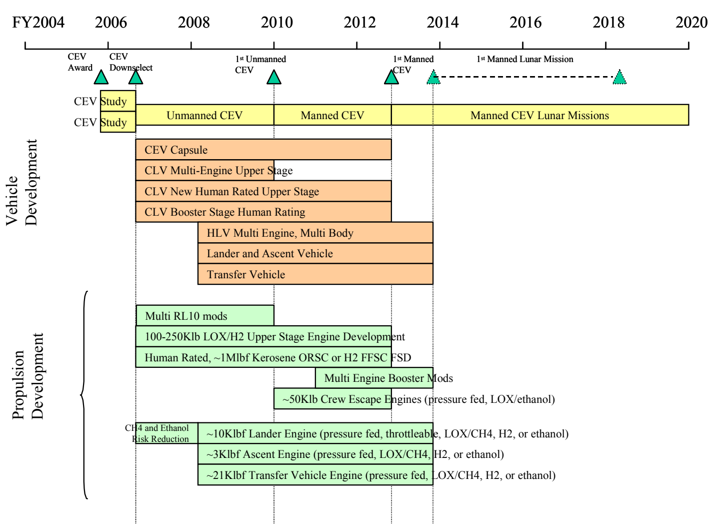

Figure 5. Project Constellation EELV Evolved

In all cases, except for the Shuttle derived concept, liquid propulsion systems are assumed. Historically, solid motors have been added to launch systems to increase payload list capability and add flexibility, and may still be required. Test requirements for solid motors were out of scope for this study, but would further challenge test capabilities to some extent.

DEVELOPMENT OF REPRESENTATIVE TEST REQUIREMENTS FOR EACH PROGRAM

The goal of the previously discussed vehicle roadmaps is to combine top-level propulsion development efforts and propulsion test requirements into a roadmap for engines, stages, and components. Specific propulsion system requirements have not been prepared yet for the programs under consideration. Assumptions therefore had to be made to provide a best estimate of propulsion system test needs against expected program needs.

To develop the propulsion test roadmaps, it was necessary to estimate a standard set of test rates and test requirements to apply to various component, engine and stage firing programs. Development efforts in the last 20 years were reviewed to determine test rates for recent U.S. and foreign programs.[22-23,25] Results are summarized in Figures 6 to 9 for major engine components, boost and upper stage engines, and rocket stages. The data are plotted in order of increasing thrust to help discern trends. In some cases, specific model numbers are not identified due to the proprietary nature of the data.

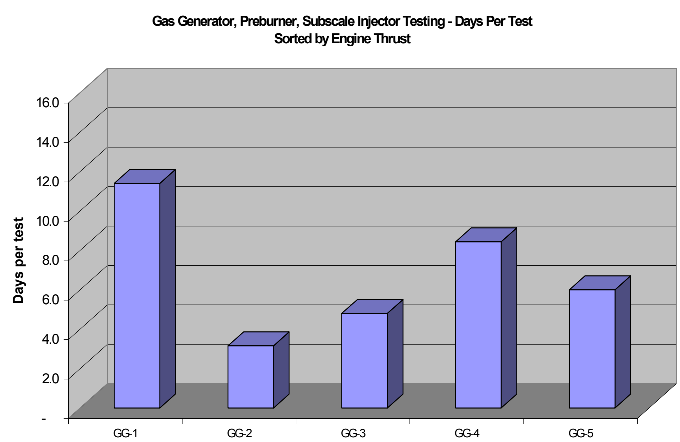

Figure 6. Historical test rates for combustion components.

Based on the figures, one can see that there is considerable scatter in the historical test rates. There are many factors that can affect test rate, including the technology readiness level, the number of failures to resolve, the maturity of the test program (test rates improve with time), the crew size, the test stand readiness, and the available funding. The estimated average test rates based on this evaluation are shown in Figure 10. The estimates do not take into account the time needed to activate and prepare a stand to receive a new engine, but they do include time for engine change out on the stand when multiple engines were tested. Based on past experience, facility activation time can be two to four years for stage tests. Also, note that the upper stage engine firing rates have historically been much higher than booster engine test rates, largely due to the ability to achieve multiple firings in a test period with restartable engines.

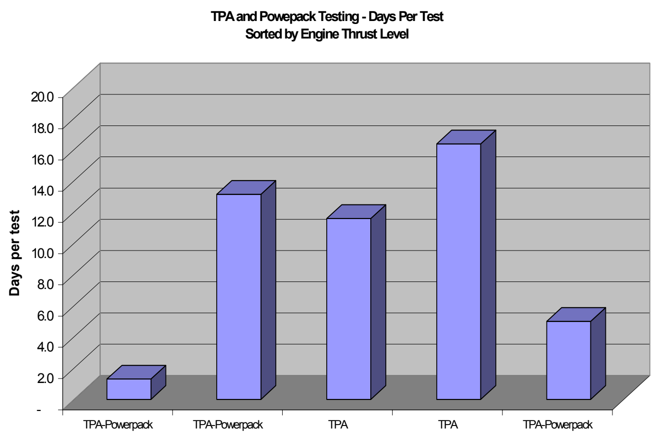

Figure 7. Historical test rates for turbopump components.

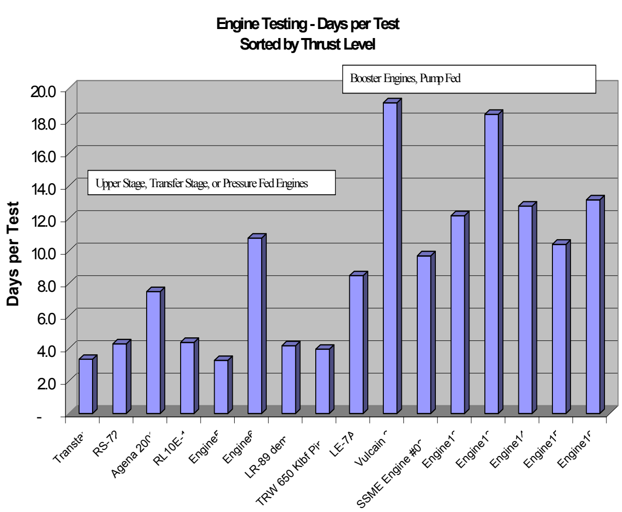

Figure 8. Historical test rates for liquid rocket engines.

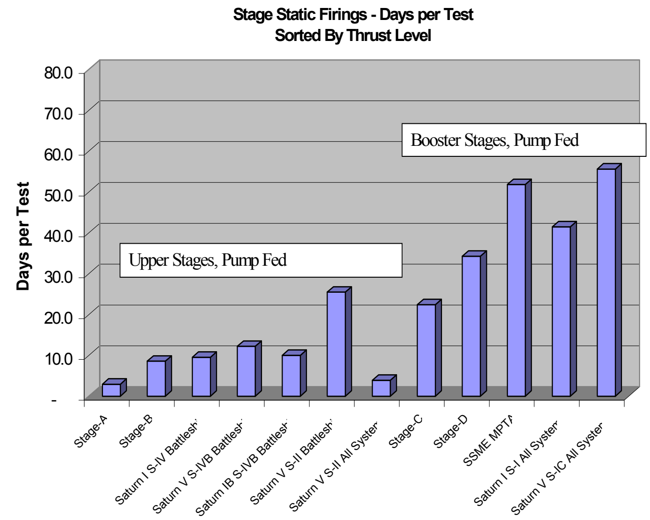

Figure 9. Historical test rates for stages.

Booster Engine	12 days per test
Upper Stage Engine	5 days per test
Pressure Fed engines	5 days per test
Preburners and Gas Generators	5 days per test
Chambers and Injectors	5 days per test
Turbopumps and Powerpacks	7 days per test
Stage Firings	25 days per test for boosters 5 days per test for upper stages

Figure 10. Estimated test rate for engines, components and stages.

Given the concept architectures in Figs. 3 to 5 and the considerations above, propulsion test roadmaps were developed for the various projected scenarios as follows. Time phasing of the component and engine testing as well as the number of test stands required to complete a test segment were based on experience, milestone constraints, and assumptions about contract awards or vehicle downselects. The number of tests was estimated using recent and historical programs. As an example, a total of 400 engine firings were used for human rated or RLV engine development based on guidance from Ref. 23. That number was reduced by 50% for non-human rated expendable vehicles based on recent trends. Required test series duration was then derived using the estimated test rates in Fig. 10. The resulting liquid propulsion test roadmaps are shown in Figs. 11a and 11b for the Shuttle derived architectures. The other roadmaps are not shown due to space limitations.

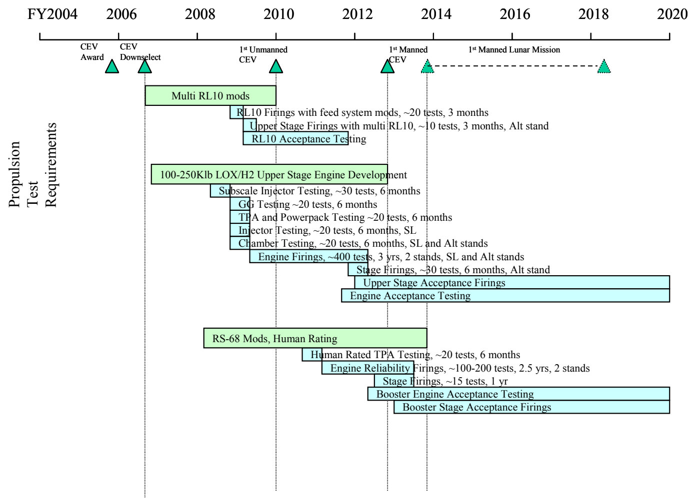

Figure 11a. Propulsion test needs for Shuttle derived solution.

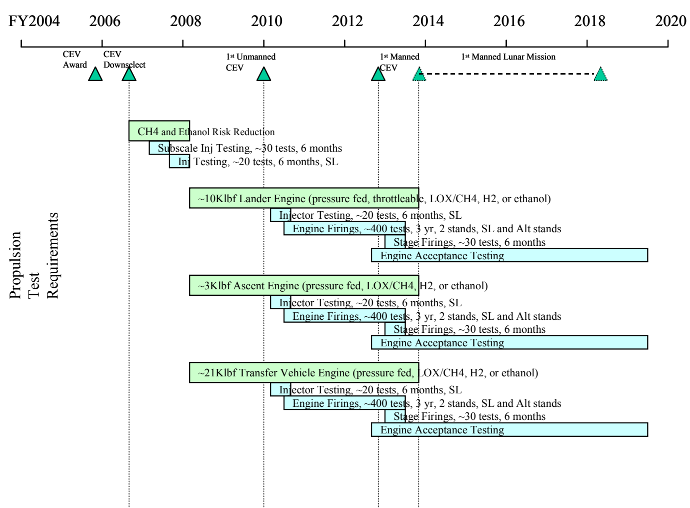

Figure 11b. Propulsion test needs for Shuttle derived solution.

Each development roadmap included component testing and stage firings as needed. In the EELV systems, a LOX/ethanol crew escape system was assumed necessary to meet crew safety requirements. The NASA in-space portion was assumed to include an orbit transfer stage, a lander stage and a separate ascent stage. It is possible that the lander and ascent stage might be combined into a single function. Thrust levels shown are estimates only and for test stand sizing purposes.

The roadmaps for space exploration all showed that there will be a high demand for test stands from 2010 to 2014 as programs overlap. The highest demand was for the EELV evolved architecture due to the development of a new human rated booster engine.

The process just described was followed for both civil and military programs to gain an overall picture of potential U.S. test needs.

EXAMINATION OF CURRENT DOMESTIC ENGINE TEST CAPABILITIES AGAINST THE TIME PHASED ENGINE DEVELOPMENT NEEDS

The roadmaps presented in the previous figures were consolidated with the other program roadmaps generated during the study. This produced a set of roadmaps for propulsion system development, engine testing, stage testing, and component testing. Consolidated roadmaps were generated for high test demand and low test demand scenarios. The end goal was to look for both gaps in test center abilities to meet anticipated needs as well as opportunities for technology transition by mapping the programs together.

The study findings indicated the following: The existing liquid rocket engine testing capability in the United States appears to be adequate to meet the anticipated U.S. civil and military needs. However, the roadmaps identified high demand for liquid rocket engine test stands beginning in 2010 and beyond that may stress test stand availability. This conclusion is drawn under several significant assumptions. The first assumption is that available stands can be converted to meet unique engine test needs such as propellant type. The second assumption is that currently mothballed stands can be re-activated as demand picks up. The third assumption is that engine thrust class is the primary factor in test capability assessment for future engine systems. Also, to fully realize the goals of the spacelift initiatives that are being proposed will require maintenance and possible upgrade of existing liquid engine test facilities in the near future.

SUMMARY

Based upon an examination of mission planner propulsion needs, test rates, and derived liquid rocket engine test demands, the following conclusions were made:

1. Several new programs are in planning and

various stages of development at this time, including NASA space exploration missions to the Moon and Mars and highly operable launch vehicles for military application, including the FALCON and ARES programs.

2. The number and type of liquid rocket engine test facilities will meet current needs of both civilian and military spacelift programs. However, as future requirements for programs evolve, these test facilities may require additional modifications of varying complexity and investment. The types of facility modifications are difficult to define at this time since they are highly dependent upon launch architectures yet to be chosen. For example, the ability to test engines using LOX/Methane propellants would require the development of new operational procedures and possibly new storage and run tanks.

3. The process of developing a new human rated engine to support the space exploration effort will involve significant testing to evaluate and certify fault detection instrumentation and software. Engine fault detection is a critical element of any crew escape system. Along with fault detection system development, there will be increased test demand for engine margin demonstration.

4. Stage acceptance testing may be required to certify a human rated vehicle for flight. Stage testing involves significant stand reconfiguration. This significant time and money investment could result in the use of a test stand for an extended period of time depending on the degree of stage testing (i.e., development and/or acceptance) required by a given program. Test stand activation and preparation can also take two to four years to be ready for testing.

5. There is a potential for high test stand usage starting in 2010 due to engine and stage test needs. Altitude stands in particular will be stressed to meet the demands. Any catastrophic test anomaly occurring during this period of high facility demand could have major time and cost impact to spacelift development.

6. Possible growth in the commercial spacelift sector could result in more demand for use of government test facilities, although the current demand does not impact facility availability at this time.

7. Rocket propulsion test road mapping is predicated on assumed funding and national priorities. Regular re-assessment of civil, military, and commercial space launch programs is needed to provide an accurate picture of future test needs and to determine whether adequate test support can be provided to new initiatives. These assessments would be best provided based on event driven changes, such as when major replanning occurs.

8. As space exploration launch needs evolve, NASA should undertake the following tasks:

    a. Determine the feasibility of using and/or modifying test stands to meet the potential high demand for altitude test facilities in 2010 and beyond.

    b. Assess required effort to reactivate sea level test stands to meet the potential high demand.

    c. Establish which alternative propellants (e.g., methane, advanced hydrocarbons, slush propellants, gels, hydrogen peroxide, etc.) have likely potential for operational system development. Query all primary test facilities to define the level of effort and associated cost to add test capability with these alternative propellants.

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